QANATS–UNDERSTANDING WORLD WATER RESOURCES

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ABSTRACT

Globally, water recourses are scarce in semi-arid to arid environments, specifically the Middle East. In order to provide civilizations with access to water, the construction of a qanat system has been critiqued. The location of most qanat success has been located in Kerman, Iran. In order to understand the history and progress of qanat technology in Kerman, Iranian geology, hydrology and climate were analyzed.

Acknowledgements

First, I would like to thank James St. John who not only exposed me to but also encouraged me to become absorbed in the geological sciences on the first day of my undergraduate career. Thank you for helping me find my passion. I would also like to thank Dr. Frank Schwartz for taking me in and helping me with all of the undergraduate research necessary to produce my senior thesis. I appreciate your patience and guidance throughout this research project. I would like to thank Lienne Sethna, my best geofriend, for her continuous enthusiasm and encouragement. Last, but certainly not least, a huge thank you to my parents for their endless love, inspiration and support during all of my endeavors.

1. Introduction

One of the world's most impressive technological achievements took place in Iran approximately 3,000 years ago (Beaumont, 1971). For the first time, people were able to utilize groundwater supplies in arid desert regions with minimal rainfall efficiently. As a result of this new idea, people now had a sustainable way to provide local fields and villages with water. This new technology is referred to as a qanat.

A qanat system is essentially a low angle (nearly horizontal) well installed into an alluvial fan. It consists of a gently sloping tunnel, which is dug horizontally, tapping the groundwater close to the water table. Most qanats are designed to capture seasonal runoff from upland areas, which infiltrates alluvial fans. Thus, placement of qanats relies on the potential for local infiltration as well as shallow groundwater accessible through dug wells.

Qanats are considered efficient water supplies because they require no power source other than gravity to maintain flow of water. Moreover, they are capable of moving water significant distances with minimal evaporative losses and pollution risk. The discharge of a qanat is a function of the productive capacity of the aquifer and the length of the water bearing section of the tunnel below the water table (Beaumont, 1971). Seasonal fluctuations in the height of the water lead to variations in discharge.

The process of construction begins by digging a vertical shaft to penetrate the permanent water table (Figure 1). This shaft is referred to as the mother well of the qanat because the depth to water in this well determines the design (Beaumont, 1971). The qanat length is measured from the mother well to the point where the tunnel intersects the ground surface, known as the qanat outlet. Alignment of the tunnel was actually quite difficult because this requires that the tunnel have a proper slope from the base of the mother well to the surface above the fields of the settlement, where it becomes a surface canal (Figure 1). If the tunnel emerges at a large distance from the settlement, the water will flow in an open channel on the surface. This surface flow will lead to evaporation and seepage. Examples of this problem are evident in eastern Iran, where only one quarter of the qanat water reaches fields.

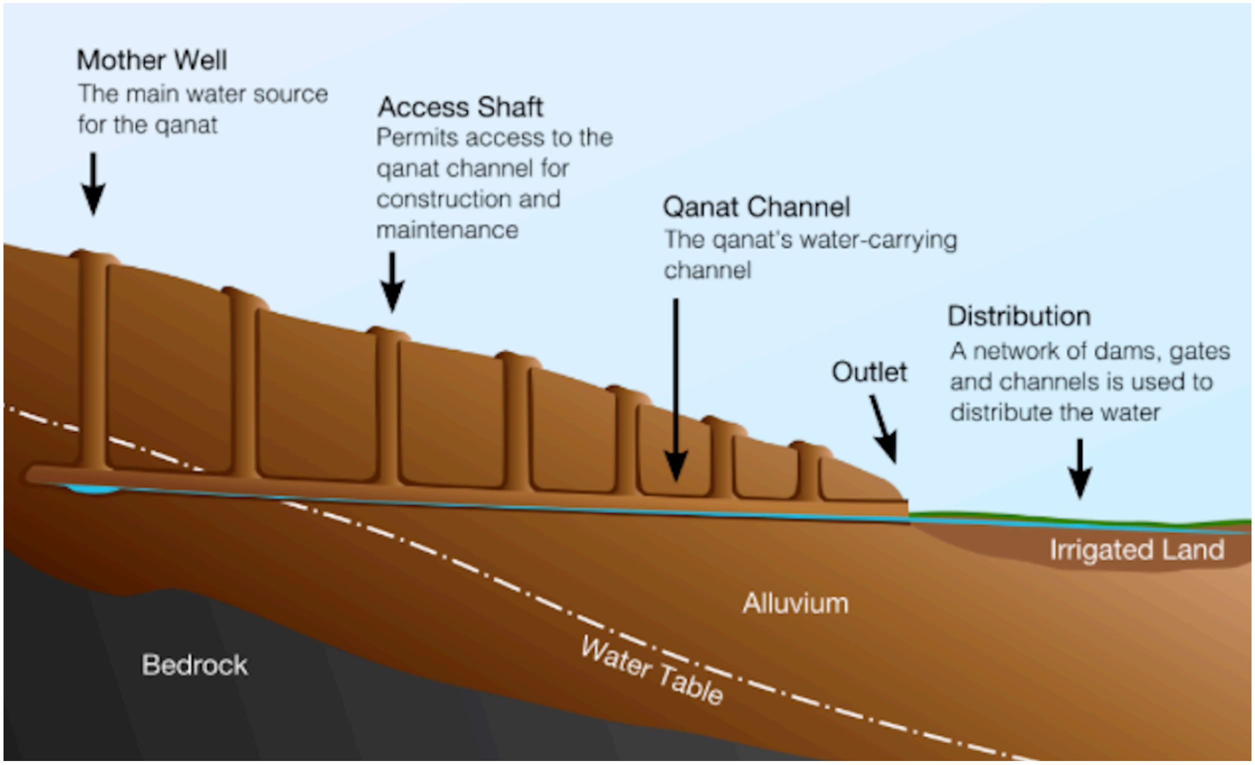

Figure 1: Cross-sectional schematic shows the essential features of a qanat (Stiros, 2006).

Another challenge in construction is achieving the proper gradient of the tunnel. If the gradient is too steep, water will erode walls of the qanat causing damages. Once gradient and alignment have been achieved, tunnel digging begins.

Digging the tunnel typically began downslope, where the tunnel is above the water table. Construction upslope from drier materials eliminates cave-ins. Clay hoops can be placed to support the tunnel roof and to prevent potential collapse in areas of soft sand. From this starting point, the tunnel is hand dug, uphill towards the mother well. Vertical shafts are placed every 50 to 100 meters, connecting the tunnel. These shafts act to provide ventilation and sediment removal during construction. The mounds of soil around these shafts on the ground surface are highly recognizable in aerial photographs and indicate the layouts of the tunnel systems (Figure 2).

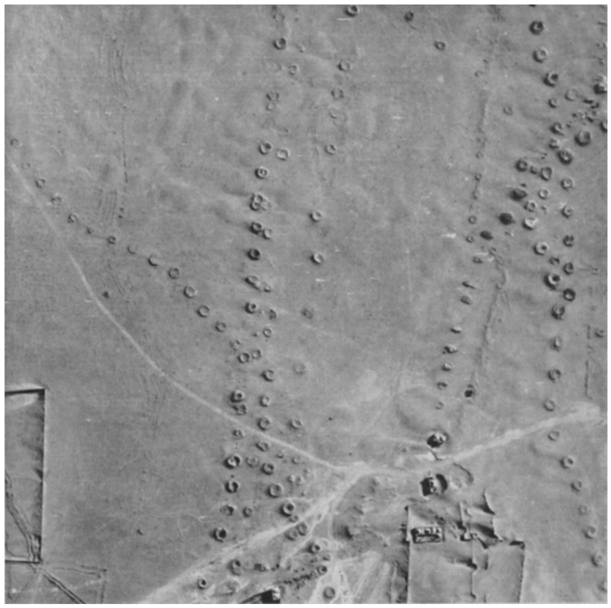

Figure 2: Aerial photo showing the surface manifestation of qanat systems in the southern margin of Kerman, Iran (English, 1968).

The building and excavating of these systems is completed by teams of workers, with only a bladed pick, shovel and lamps. On average tunnels are about one meter wide and 1.5 meters high.

The length of a qanat is dependent on the slope of the ground surface as well as the depth and inclination of the water table. On average, qanats are short in the more steeply sloping alluvial deposits at the foot of mountains whereas they tend to be very long in desert areas where the ground slopes minimally. There is also a possibility of twin qanat systems built side-by-side

(English, 1996). Twin systems allow for a greater amount of water to reach a village and they also function as a safety network. Side-by-side systems allow workers to escape flooding and cave-ins. Qanats take years to construct and with an estimated 1960 cost of approximately 10,000 dollars per kilometer (English, 1996).

Spread of Qanats

Conventional thinking is that qanat technology spread from that part of the world known now as Iran along trade routes to the arid countries of Africa, Asia, and beyond. Some authors like Magee (2005) think that the oldest qanats occur in Oman with development of the concept in arid countries at about the same time. It was surprisingly long-lived only fading from use in the last century, as water well drilling technologies emerged. One of the most intensively developed areas for qanat systems is Iran.

Broad similarities in the climate and geology across the Middle East naturally promoted the spread of qanats or their indigenous discovery. Some 3,000 years ago the peoples of ancient Iran had possible ties with the mines and trading routes in the region. Evidence supporting the spread of technology is based on the very similar designs of early mining adits as compared to the horizontal chambers of qanats. The extent of spreading of this technology is remarkable. For example, Syrian cities, especially those located near the Tigris River, relied on qanat systems for their drinking water. Qanat systems became widely spread in Persian territory as early as 248 B.C. Qanats are found in North Africa, parts of the Americas and many other countries.

Let me examine the spread of qanats in more detail. The initial diffusion out of Iran proper took place in the period when the Persian empire extended from the Indus River to the Nile (English, 1996). Qanat technology was carried to the west as the Persians moved west across the Fertile Crescent to the shores of the Mediterranean and southward to Egypt and Saudi

Arabia. East of Iran, qanats are used in Afghanistan, Central Asia and East Turkestan. Qanats were used in western China in the second century B.C. Likely, the spread of qanat technology with time, was related to the spread of Islam across North Africa into Spain and the Canary Islands, during the seventh and eighth centuries A.D. Qanat systems were introduced into the Western Sahara and historical Jewish homelands. Today, this region has more than 1,500 kilometers of qanat tunnels. Arab culture influenced the spread of qanats into Europe. Qanat technology has made human settlement achievable in marginal areas all over the world (Beaumont, 1971).

Why Iran?

Iran is typically identified as the one place with the most qanats. The number of qanats in Iran probably exceeds those in all the other areas combined. Even in modern times, up to about 1960, a majority of the Iranian cities relied on qanats for much of their domestic as well as irrigation waters (English, 1996). Even today, an estimated 15 million acres of cultivated land, is watered by around 37,000 qanats (English, 1996). The total discharge of these qanat systems has been estimated at 20,000 cubic meters per second.

The obvious question then is why Iran ended up as the home for this innovative technology as compared to other arid lands in Africa, Middle East and elsewhere. The study here sets out to answer the question of why qanat systems grew up in Iran. My hypothesis is that features of the physical setting necessary for qanat construction probably existed in Iran to an extent that somehow fostered the technology. Much of this paper then is concerned with identifying and analyzing to what extent the necessary components, including the geology and hydrology, and climate are represented, as well as the technical/intellectual skills required for the actual construction. To provide a local perspective, I have focused on the region of Kerman, Iran and what conditions exist there to make qanats successful over time.

2. Methods

The methods utilized in this study involve compiling the results of research by others in order to assess and analyze the necessary components which allow for the success of Iranian qanat systems. Analytical steps involve the application of databases and resources in order to manipulate geological, hydrological, dendrochronological, and climatic data of the studied area. The potential of each component and its relationship with one another were then analyzed and identified.

The descriptions that follow examine Iran more broadly. However, as mentioned there is a local focus on an area of south-central Iran around the city of Kerman. This city with a present population of around 600,000 is located in the Kerman Basin of Iran at an elevation of approximately 5,680 feet in southeast Iran (Figure 3) (Falcon, 1974).

Figure 3: Map showing the major cities of Iran. Kerman is indicated by the arrow on the map.

3. RESULTS

As qanats developed, they were better adapted for some areas rather than others. Not surprisingly, there are some areas which are highly populated with these systems in comparison to others. Almost all of the qanat systems in Iran are associated with large alluvial fans. Most of the environments occur in a circular zone around Great Kavir in central Iran (salty lowlands middle of the country) (Figure 4). This has been referred to as the Central Plateau groundwater province of Iran.

The tectonic setting of Iran is complex (Figure 4). This is not surprising given the active orogenic process driven by the movement and collision of Arabian and the Eurasian plates. The process of collision occurred as the Arabian plate moved underneath the Eurasian plate during the Miocene and Pliocene epochs. Collision on a smaller scale continues to take place today.

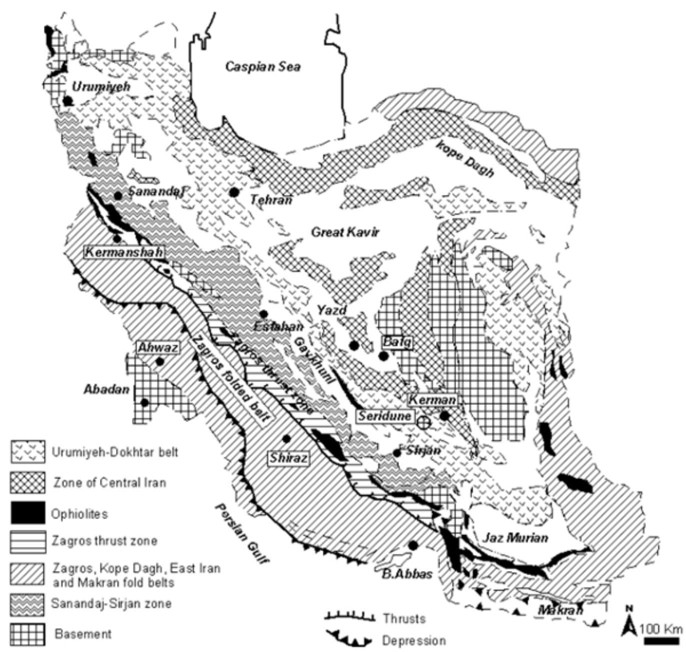

Figure 4: Map of Iran, showing geologic zones (Bahrami, 2013).

Major tectonic elements in Iran include the various deformation zones associated with the Zagros Mountain range that extends across a total of 1,600 kilometers in length and more than 240 kilometers wide (Figure 5). Also shown on Figure 5 are the Alborz Mountains located at the southern end of the Caspian Sea. Although relevant to the development of qanats in Iran, this range is not considered in detail.

Regional Geology Zagros Mountains

The Zagros Mountain Range is Iran's largest mountain range as it stretches south and west from the borders of Turkey and Russia to the Persian Gulf. The mountain ranges near the city of Kerman are generally considered to be eastern outliers of Zagros range. The Zagros range is situated mostly in Iran, forming the western boundary of the Iranian Plateau (Figure 6).

Figure 5: Topographic map displaying the Zagros Mountain Range through Iran (Kowsar and Kowsar, 2012).

The oldest rocks of the Zagros, found near the highest peaks, are Precambrian and Paleozoic in age. The highest point in the mountain range is known as Mount Dena, with an elevation of 4,409 meters above sea level. The Zagros range is divided into two distinct zones of deformation, occurring on each side of the north south strike-slip fault. The topography varies on either side of the fault, due to different basal friction on each side. Sedimentary cover in the southeastern Zagros is deforming above a layer of rock salt, which acts as a ductile decollement with low friction. In the northwestern region of the Zagros Mountains, the salt layer is missing or exists very minimally. This pattern of variability produces higher topographic relief with a narrower zone of deformation in the northwestern Zagros and a wider zone of deformation and lower topography throughout the southwestern portion of the Zagros range. As a result of successive erosion, the linear ridges of the Zagros Mountains formed. More specifically, the softer rocks, such as mudstone and siltstones, were removed leaving the more resistant limestone and dolomite layers. Other common features of the Zagros Mountains are salt domes and salt glaciers.

The predominant rock-type of the Zagros Mountain range is limestone. Figure 6 is a geological column for the Zagros Mountains.

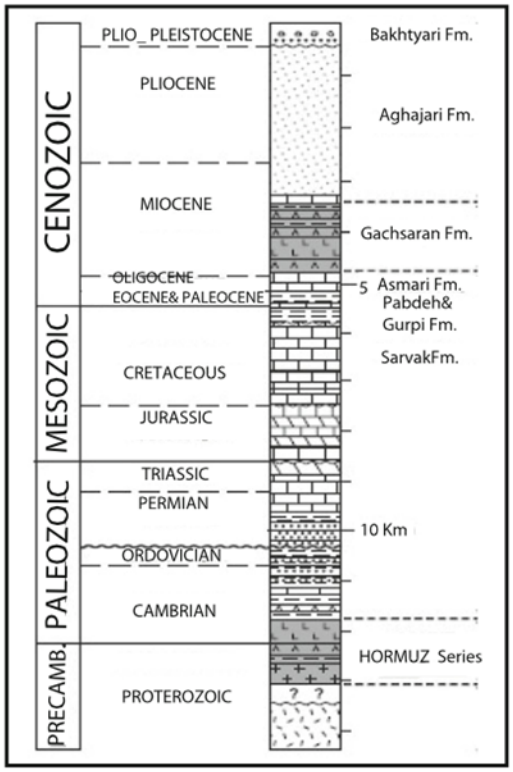

Figure 6: Zagros Mountain Range stratigraphic column (Bahrami, 2013).

The elevated portion of the Zagros consists of Paleozoic rocks that are found along the main fault. On both sides of the fault, there are Mesozoic aged rocks and a combination of Triassic and Jurassic aged rocks, surrounded by Cetaceous aged rocks.

The Zagros Mountains are aligned with a northwest to southeast trending pattern. The two major subdivisions of the range are known as the elevated Zagros and the folded Zagros. The elevated portion forms the northeastern mountains and the folded fraction of the mountains stand in the south and west of the elevated Zagros.

In the Zagros range, synclines have been filled by Miocene aged gypsiferous clays and marls overlain by alluvial deposits. There are two main factors which aid in the determination of the geological character of a basin, namely the deposition of thick lacustrine layers and the filling of basins with alluvial deposits. Alluvial aquifers underlie 420,000 square kilometers of Iranian land which can store around 5,000 cubic kilometers of groundwater. This number is eleven times the mean annual precipitation of Iran and one hundred and fifty times the initial capacity of man-made reservoirs (Bahrami, 2013).

Most relevant to the development of qanats are the alluvial deposits that exist within intermountain valleys. Water can be stored in aquifers for long periods of time because evaporation from these underground reservoirs is very low. Alluvial deposits exist within very deep and wide alluvial strata, south of Alborz and east of Zagros Mountain Range on Iranian Plateau and in inter-mountain valleys. Within these regions, water is stored in aquifers.

Most aquifers in the folded zone of the Zagros Mountains form a broad highland aquifer (Bahrami, 2013). The aquifer in this folded zone exists due to the following characteristics. The aquifers are “sandwiched” between two thick, low permeability formations. The rocks from the poorly permeable overlying formations are eroded from high elevation parts of the anticlines and are mostly exposed at the foot of the anticlines or buried under a thin alluvium. Lastly, the flow from one anticline to the parallel, adjacent anticlines is unlikely because formations are typically buried under a very thick overburden. In conclusion, the aquifer boundary is limited to the overlying and underlying impermeable formations or adjacent alluvium (Bahrami, 2013).

A particular focus is the city of Kerman in southeastern Iraq. As implied by the geological map (Figure 8), Kerman is located in a broad valley, nestled among larger mountain ranges at an elevation of 1762 m asl. In the vicinity of Kerman, mountain elevations can exceed 4400 m asl.

The general area where the city is located is underlain by soluble subsoil and alluvial deposits overlying highly fractured Cretaceous limestones. Deserts and arid lands in the northern parts consist of more than 30 percent of the total areas of Kerman province. The oldest rock series of the known area is the Morad Series of Upper Neoproterozoic to Infra-Cambrian. The lithology of this series is composed of slightly metamorphosed arenite, greywacke, siltstone, as well as turbiditic layering. The upper unit of the Neoproterozoic to Infra-Cambrian is given the name of the Rizu Series. The lithology of the Rizu Series consists of weakly metamorphosed conglomerate, calcareous arenite and rhyolitic tuff. Paleozoic rocks within Kerman are weakly metamorphosed dolomite, quartzite and marble. Units of Triassic and Jurassic aged rocks are sandstone, siltstone, and shale with minor limestone beds. The rock exposures of the Cretaceous are the most widespread units in the area. The basement is composed of Lower Cretaceous limestones, and the upper units are part of the Upper Cretaceous reef limestone. Most of the lower Tertiary units include andesite, basalt, and pyroclastic rocks. Within the area, Quaternary units include Older Dasht, Younger Dasht and Recent Dasht. The Older unit consists of old dissected alluvial fans, gravel fans and terraces, with sharp fault escarpments. The Younger unit includes younger undissected gravel fans and the Recent unit includes recent alluvium which has been transported by neighboring bed rocks (Atapour and Aftabi, 2002).

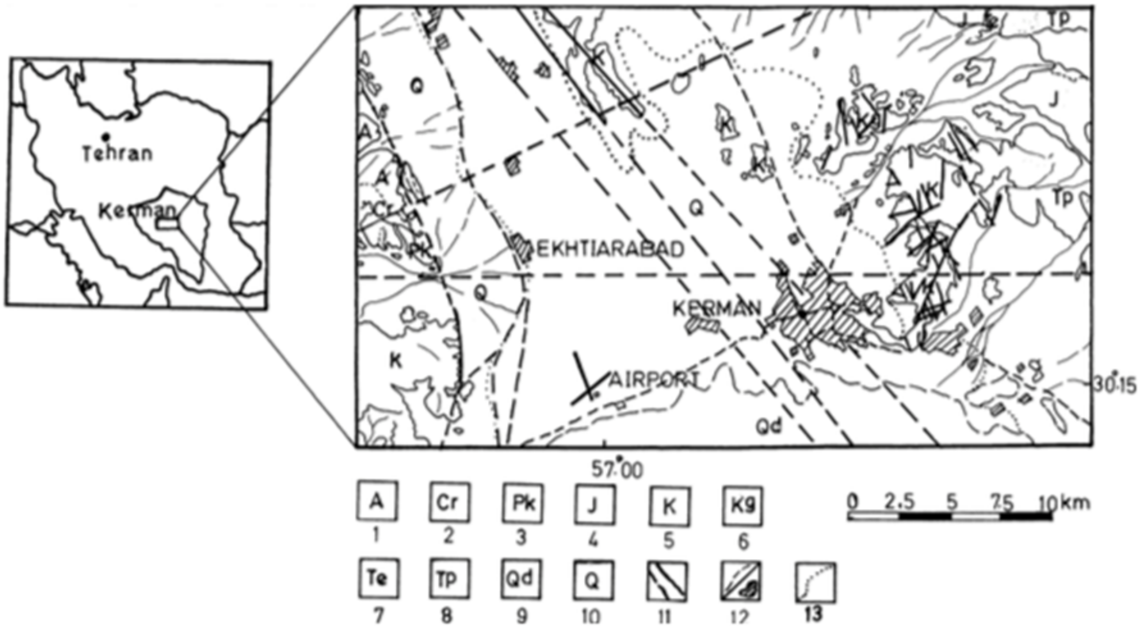

Figure 7: Regional geology of Kerman city (Atapour and Aftabi, 2002).

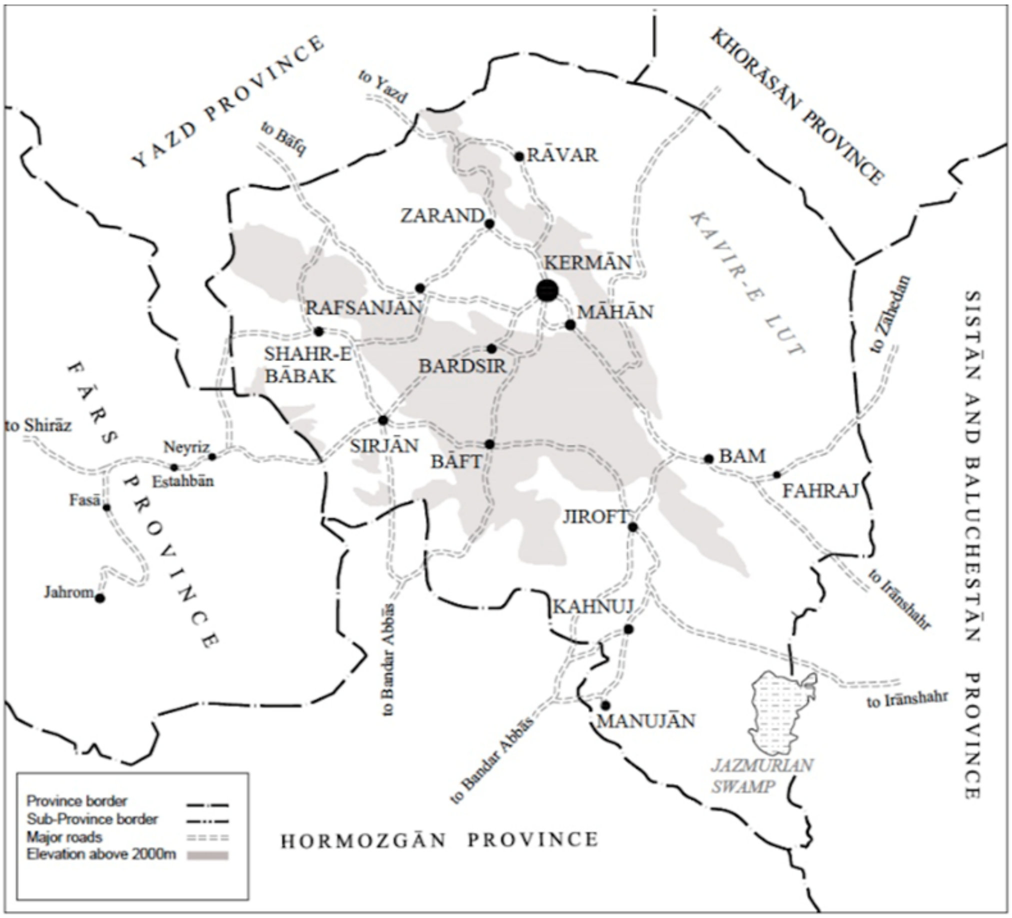

Figure 8: The map provides an overview of the country's provinces, to better grasp the geographical regions which surround the city of Kerman, Iran.

Climate and hydrology

The climate of Iran is semi-arid to arid. The average rainfall is minimal and decreases towards the southeast portion of the country (Figure 9). The main exception are the higher precipitation and snowfall recorded in the mountains of the central Zagros region, commonly >500 mm/yr. Precipitation and snowfall result from weather systems from the west bringing moisture out of the Mediterranean region. Precipitation is more abundant at higher elevations, which facilitates the recharge of alluvial fan systems during the wet season, typically occurring in winter. With this being said, throughout the north and western regions of Iran, different processes work to produce rather different amounts of rainfall. The rainfall variations are dependent upon coordinate locations of cities and to elevation. It is evident from the map that mountain ranges serve locally as key “water catchers” often yielding > 500 mm/yr. In areas without substantial mountains, for example, northern central Iran has the estimated annual rainfall is <100 mm. millimeters, while the central region of the country experiences an annual precipitation of less than 100 millimeters (Figure 11).

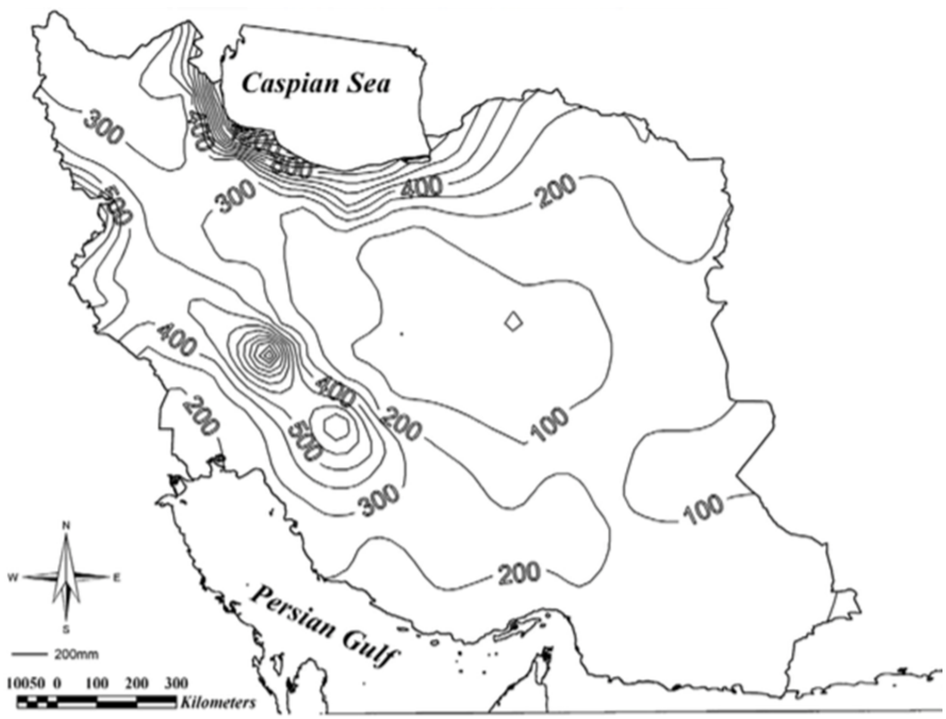

Figure 9: Map of annual rainfall of Iran, aiding in the visualization of the rainfall relative to elevation (Modarres and Sarhadi, 2011).

As indicated on Figure 9 precipitation at Kerman is much lower. Table 1 provides mean monthly precipitation and temperature over thirty years (English, 1966). From this table the annual average rainfall was determined to be 142 mm in Kerman. There is an obvious wet period in winter from December to March. Precipitation ranges from 18.4 to 32.0 mm/month during this time with precipitation occurring on only four to six days per month. From June to October, precipitation is negligible. The city of Kerman experiences hot summers and mild winters. Temperatures are rarely below zero and in summer, with maxima >35^{o}C.

KERMAN CITY TEMPERATURE AND PRECIPITATION*

Month	Mean Temperature (°C)		Mean Total Precipitation (mm)	Mean Number of Precipitation Days
	Daily Min.	Daily Max.		
January	-4.0	11.8	29.0	5.1
February	-1.1	14.2	26.7	4.6
March	3.4	18.6	32.0	6.0
April	7.9	23.8	19.5	4.4
May	12.0	29.8	8.6	2.0
June	15.6	34.8	0.5	0.3
July	17.0	35.5	0.7	0.3
August	14.2	34.0	0.6	0.2
September	9.8	31.0	0.3	0.1
October	4.8	25.7	0.7	0.3
November	-0.7	19.2	5.1	1.5
December	-3.6	14.1	18.4	3.5

*The data are monthly averages for the 30-year period 1961-90.

Table 1: Kerman, Iran climate variations displayed by temperature and precipitation (English, 1966).

Kerman Province is divided into two district macroclimates. The upland north, referred to as the Sardsir and the lowland south, Garmsir. These are two terms that identify the regional entities which allow for the formation of a geographical contrast.

The higher precipitation of the central region of the Zagros gives rise to rivers that flow irregularly into bordering arid zones. In order to understand climate and precipitation within Iran better, knowledge of past climate variability of the region is of great importance.

Due to an inadequate distribution of meteorological stations through the Zagros region, there are limitations on the availability of information. An accurate method to provide proxy data for past climates of Iran is dendrochronology (Azizi et al., 2013). The central Zagros range is an important site of oak forests in Iran. Studies show that oak trees in Iran provide dendroclimatological data, allowing for the reconstruction of paleoclimates. One dendrochronology study in Iran used two types of oak trees, *Quercus infectoria* and *Quercus persia*, to form a master chronology (Azizi et al., 2013). The data from tree-ring collections derived from cores were cross-dated using visual and statistical tests using appropriate software. After numerous steps and processing, a linear regression model is used to reconstruct the precipitation during the months of October through May thereby displaying dry versus wet periods.

Soils

Soils within Kerman Basin also represent the dry climate. Most soils are thin, poorly developed and unstructured. The arid environment is portrayed through weathering, as mechanical weathering dominates and chemical weather takes place slowly (English, 1966).

Qanats at Kerman

A major focus of this study is the city of Kerman and qanats found there. The actual province of Kerman is known for long qanats. For example, at Zarand, located north of the city of Kerman, Beaumont (1971) reported five qanats longer than 20 km with the longest in excess of 30 km. One of the most famous long qanats in Kerman Basin runs for an estimated twenty-nine miles to the city of Kerman (English, 1966).

Studies by Magee (2005) at Tepe Yahya, located about 180 km south of Kerman, provides bounds on when and why qanats developed in this part of Iran. According to Magee, qanats likely originated across the Persian Gulf in modern-day Oman. Towards the end of the second millennium BC (i.e., 1100 BC), archaeological evidence pointed to an obvious expansion of settlements, including Tell Abraq and Muweilah. The main driver of this growth was the emergence of the qanat technology, which provided the key to adapting to an increasingly arid climate. He suggests qanats at Tepe Yahya in southeastern Iran were several centuries younger, perhaps around 800 BC. So while the home of the original invention could be in dispute, there is no doubt that Iran was fertile ground for the promotion and enhancement of qanat technologies.

Kerman is a good example of how qanats enabled the occupation of the dry desert lands among the high ranges of the eastern extension of the Zagros Mountain belt. Figure 10 is a map showing the distribution of qanats around the city of Kerman. Generally, qanats were designed to move water towards Kerman from nearby alluvial fans. Shorter qanats are less than 8 km in length, and occur beneath the alluvial fans at the foot of Kuhi Darmanu to the north and to the east of Kuh Paiyeh. These shorter systems carry water to the city of Kerman.

Longer qanat systems in Kerman, cross the central plain from the alluvial fans of the Kuhi Jupar (Figure 10). Mother wells of these qanats can be 50 m or more deep with associated tunnels extending northward from the area of Kuhi Jupar (English, 1966).

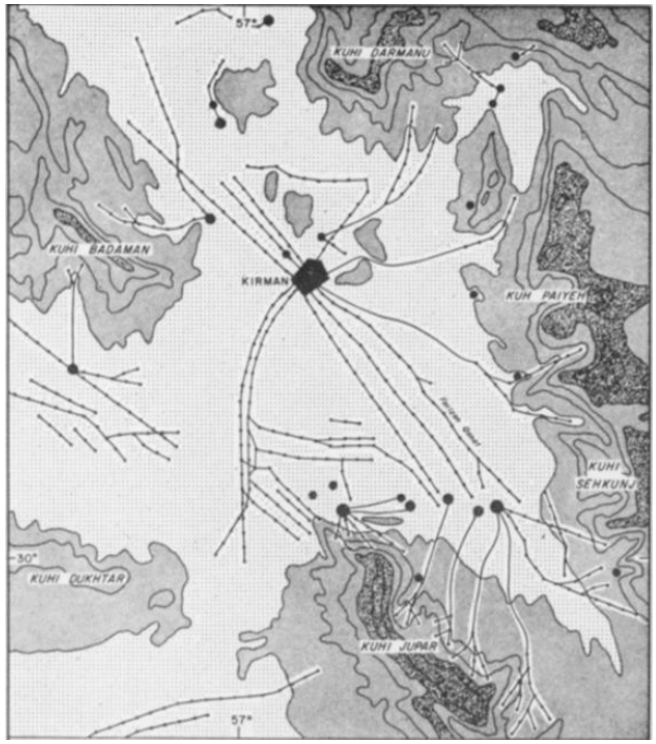

Figure 10: Map showing the qanat tunnels which radiate toward the city of Kerman (English, 1966).

Although the exact number of qanats which carry water to the city of Kerman is uncertain, there is a high density of qanat tunnels in the Kerman Basin. Settlements in the Basin are located high on the alluvial fans. For centuries qanats were the only source of water in these towns. It has only been in the 20th century that wells were used because the water table lies 100–125 m beneath the ground surface.

Societal Knowledge for Qanat Construction

Previous sections examined key elements of the physical setting necessary for success in the development of a qanat. There is also another factor to be considered and that is what level of "art" is necessary in a society to design and construct a qanat. Previous sections have discussed mother wells and the associated tunnels. Clearly, the digging was primitive with only hand tools to dig with and baskets to move excavated materials to vertical wells. Simple windlasses likely provided the mechanical advantage required to move material to the surface. What is surprising is the depth of certain of these systems. Beaumont (1971) found mother wells with depths of 50 to 100 m to be relatively common. A few were dug to 150 m and in one or two instances the mother well approached 300 m. Most tunnels were 5 km or shorter, but as mentioned, several were 10 to 20 km and one or two were 30 km or longer. It appears that the minimal ability for digging and moving materials was overcome by extraordinary patience and determination.

Qanats do in fact have a complex and complicated design that required an ability to make measurements and do calculations. Although not a major emphasis of my thesis I examined what was needed in terms of societal capacity to facilitate the design, for example instruments and techniques.

The first step in the excavation of a qanat is to determine the location of the mother well. The mother well is located in an area from which ground water likely occurs in an aquifer at relatively low depths (Stiros, 2006). If locating the mother well is successful, the next step is to measure the distance from the mother well to the qanat outlet. This allows for the length of the underground tunnel to be estimated. The gradient of the tunnel between two points is defined by the change in elevation from the horizontal to the point at which the mother well has pierced the deepest part of the aquifer, divided by the length of the entire qanat described by the following equation:

$$g = \Delta h / S \tag{1}$$

where g is the gradient, Δh and S are the elevation difference and distance respectively (Stiros, 2006).

A second equation provides the variances in the gradient with:

$$\sigma^2_g = (\Delta h^2/S^4)\sigma^2_s + (1/S^2)\sigma^2_{\Delta h} \qquad (2)$$

where σ^2_g,σ^2_s, $\sigma^2_{\Delta h}$ indicate the variances of g, S and Δh. Equation (2) shows that the gradient depends mainly on the accuracy in estimation of the changes in elevation (Stiros, 2006). Therefore, a successful qanat design is dependent on the accuracy in the determination of the elevation differences between the aquifer and the qanat exit. The average and the local gradient of the qanat should exist between the gradient minimum and gradient maximum values to ensure steady, stable water flow. This leaves us with an equation for a height range, which equals the difference of the gradient maximum and gradient minimum multiplied by the qanat length:

$$t_{\Delta h} = (g_{max}-g_{min})S \qquad (3)$$

This corresponds to a maximum error limit in the design and the tolerance in the leveling measurements (Stiros, 2006).

Modern investigation and research suggests that ancient techniques used in leveling were similar to modern day surveying. Modern tools consist of bubble levels, telescopes and automatic compensators which allow for nearly absolute horizontality (Stiros, 2006). In the past, primitive tools were used to construct qanat systems. Such techniques have shown to give fairly inaccurate readings and data, especially over long distances.

A considerable problem for underground surveyors, especially in arid environments, are systematic errors (Stiros, 2006). These consist of a refraction effect, causing optical ray paths to curve rather than remain as straight pathways. A second issue is that errors accumulate over extensive distances and magnify. Conclusions show that the high accuracies of early workers were a result of being able to control the leveling errors on a basis of redundant observations and techniques which permit randomization of systematic errors.

Clay tablets (~1800 to 1600 BC) recovered from modern-day Iraq and related to the Babylonian empire show that civilizations of the day were capable in mathematics. The knowledge base included algebra, cubic/quadratic equations and Pythagorean geometry. Thus it appears that once the qanat idea was discovered that the rudimentary surveying methods discussed above could be used.

4. Discussion

The success of a qanat system requires that the physical setting be suitable, and conducive to the actual construction. In Iran, it is clear that tall mountains are extremely beneficial in magnifying the otherwise limited precipitation. While ancient societies likely knew little about groundwater, they could observe snow covered peaks and observe runoff and the very occasional stormflows moving along channels on the alluvial fans. At Kerman, qanats are more numerous to the southeast perhaps reflecting the likely tendency from the semi-circular distribution of mountains to maximize the drainage. Qanat tunnels sometimes follow ephemeral stream channels where the water table is likely closest to the surface.

Another critical requirement of the system is the alluvial fan, which is developed at the base of most mountains. By virtue of the rock rubble that makes up these fans, they tend to permeable gravels and sands, supporting relatively large rates of infiltration. Thus, mountain runoff has a placed to be stored away from the ground surface with minimal loses due to evaporation. Because of the high permeability of the sediments in the alluvial fan, only a relatively short length of a qanat needs to be below the water table to provide large quantities of water. Moreover, the coarser rock framework at the head of alluvial fans is capable of resisting piping and associated tunnel failure that could occur, for example, with finer sand.

The severe difficulty in actually constructing a qanat system was also a “blessing in disguise” for it ended up contributing to the overall sustainability of the groundwater supply. Most of the tunnel system of qanat ends up above the water table, given the difficulty in excavating below. As a consequence, qanats are highly inefficient wells with yields that would be self-limiting given several dry years in a row. In essence, they are limited to removing only a small quantity of groundwater close to the water table. While it is possible to deepen a qanat tunnel system to enhance flow, it becomes a formidable task because of the large quantities of earth to be moved. The modern groundwater wells that have replaced the qanats in Kerman and other places are now actively mining the groundwater.

So why did so many qanats end up in Iran? Although there is perhaps some controversy about exactly where the idea of qanats was born, Iran was the nexus of qanat development. Given the seasonal character of the rainfall in parts of Iran and the hot summers, expansion of populations beyond just a few individuals would have required an ability to store the meager precipitation there, except perhaps in the Zargos Mountains. The critical elements for qanats to work is high mountains with some capacity to increase precipitation with elevation and perhaps the possibility of storing some precipitation as snow. Iran is a relatively mountainous country as compared for example to other dry areas like the Saharan North Africa.

Beaumont's regional work showed that most qanats were constructed in areas receiving 100 to 300 millimeters of precipitation. During the growing season, there is even less water so that without qanats dryland farming would be impossible. Being able to capture groundwater stored in the subsurface, qanat systems facilitated the sustainable cultivation of arid lands for many centuries. But as this thesis shows, qanat success is dependent on the engineering characteristics of alluvial fans for constructing tunnels and hydrogeological conditions facilitating groundwater flow to those tunnels.

The city of Kerman resides in a valley, surrounded on three sides by mountains. The Zagros near the city have an elevation high enough to trap moisture. Due to tectonic activity, the Zagros mountain range exists at an elevation of over 4,000 meters. Rainfall on highly elevated mountains as well as winter snow on the mountain tops allow for the use of both runoff and meltwater.

5. Conclusions

Iran is the place where qanat technology enabled ancient peoples to populate an otherwise inhospitable desert environment with summer temperatures commonly in excess of 35°C. The tectonic setting typified by a plate boundary created high mountains which act as water catchers to magnify the meager seasonal winter precipitation that moves eastward out of the Mediterranean. It was only in the middle of the 20th century, after nearly two millennia of service, when qanat systems were finally supplanted by modern water wells in Iran. Unlike our modern systems, qanats were in many regions completely sustainable.

Recommendations for Future Work

This project would benefit in the future with a variety of additional steps. The researched area could be expanded to include other areas, especially in southern Libya and Algeria. Within the country of Iran more needs to be done in describing the climate better and integrating knowledge of qanats in different parts of the country. A different step could be to regionally analyze the geology of other countries in comparison, with more detail.

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